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Probing the Dark Ages with Metal Absorption Lines

S. Peng Oh
Theoretical Astrophysics, Mail Code 130-33, Caltech, Pasadena, CA 91125, USA

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ABSTRACT

Recent observations of high redshift quasars at $z \sim 6$ have finally revealed complete Gunn-Peterson absorption. However, this at best constrains the volume-weighted and mass-weighted neutral fractions to be $x_{\rm HI}^{\rm V} \geq 10^{-3}$ and $x_{\rm HI}^{\rm M} \geq 10^{-2}$ respectively; stronger constraints are not possible due to the high optical depth for hydrogen Lyman transitions. Here I suggest certain metal lines as tracers of the hydrogen neutral fraction. These lines should cause unsaturated absorption when the IGM is almost fully neutral, if it is polluted to metallicities $Z \sim 10^{-3.5} - 10^{-2.5} Z_{\odot}$. Such a minimal level of metal pollution is inevitable in the middle to late stages of reionization unless quasars rather than stars are the dominant source of ionizing photons. The OI line at 1302 Å is particularly promising: the OI and H ionization potentials are almost identical, and OI should be in very tight charge exchange equilibrium with H. The SiII 1260 Å transition might also be observable. At high redshift, overdense regions are the first to be polluted to high metallicity but the last to remain permanently ionized, due to the short recombination times. Such regions should produce a fluctuating OI and SiII forest which, if observed, would indicate large quantities of neutral hydrogen. The OI forest may already be detectable in the SDSS $z = 6.28$ quasar. If seen in future high-redshift quasars, the OI and SiII forests will probe the topology of reionization and metal pollution in the early universe. If in additional the HI optical depth can be measured from the damping wing of a high-redshift gamma-ray burst, they will yield a very robust measure of the metallicity of the high-redshift universe.

1 INTRODUCTION

Recent spectroscopic observations (Becker et al 2001; Pentericci et al 2001; Djorgovski et al 2001) of high-redshift quasars discovered by the Sloan Digital Sky Survey (Fan et al 2000, 2001a) have revealed long gaps in the spectra consistent with zero transmitted flux. This long-awaited detection of the Gunn-Peterson effect may herald the observational discovery of the reionization epoch. However, the high oscillator strength of the hydrogen Lyα transition means that complete Gunn-Peterson absorption is expected even for a highly ionized intergalactic medium (IGM). The strongest constraint comes from the Lyβ absorption trough, due the weaker (by ~ 5) oscillator strength of Lyβ. From the $z = 6.28$ quasar observed by Becker et al (2001), Fan et al (2001b) conclude that at $z \sim 6$, the lower limits on the mass-weighted and volume-weighted neutral hydrogen fraction are $x_{\rm HI}^{\rm M} > 10^{-2}$ and $x_{\rm HI}^{\rm V} > 10^{-3}$ respectively, larger by almost two orders of magnitude from $z \sim 4$. Studies interpreting the observations conclude that the observed absorption troughs are consistent with the tail end of reionization, or post-overlap phase after individual HII regions have merged (Barkana 2001; Fan et al 2001b). However, due to the rapid or phase-change like nature of reionization in standard scenarios (Gnedin 2000; Razoumov et al 2001), the "dark ages" or pre-overlap phase, when a substantial fraction of the hydrogen in the universe was neutral, is likely not far off. The spectra of the $z = 6.28$ quasar suggests a very rapid evolution in the effective optical depth and thus the ionizing radiation field and effective neutral fraction (Fan et al 2001b). This implies that a slightly higher redshift quasar may indeed lie within the pre-overlap era.

Unfortunately, even if such a quasar is discovered, we may not learn anything new about the pre-reionization epoch. The hydrogen Lyman-series absorption trough saturates fully for a neutral hydrogen fraction at mean density $x_{\rm HI} \sim 10^{-4}$; because the transmitted flux declines exponentially with an increasing neutral fraction, we do not have the power to distinguish between an almost fully neutral IGM and one with only a tiny neutral fraction. As the IGM becomes almost fully neutral we might observe the red damping wing of the Gunn-Peterson trough (Miralda-Escudé 1998). Unfortunately, the highly luminous quasars presently observed probably ionize their surroundings on several Mpc scales; the consequent reduction in optical depth precludes observation of the red damping wing (Cen & Haiman 2000; Madau & Rees 2000). The only hope of detecting a damping wing would be to discover objects that ionize only a small region of the surrounding IGM: either a high-redshift gamma-ray burst (which has a very short duty cycle) or less luminous quasars or galaxies (which can be detected through gravitational lensing, Ellis et al 2001). Alternatively, one might hope to detect the Lyα halo surrounding a high-redshift source as Lyα photons scatter and redshift in the surrounding neutral IGM (Loeb & Rybicki 1999). This also suffers from the difficulty that sources tend to ionize their surroundings; furthermore, the low surface brightness of the halo implies that detection is likely only possible with NGST.

What can be done with present-day technology? Clearly, we need absorption-line probes which are still unsaturated when the IGM is predominantly neutral. This is possible if the absorbers are much less abundant than hydrogen or have very small oscillator strengths. They should have ionization potentials similar to that of hydrogen in order to trace the HI fraction as faithfully as possible. In addition, their absorption lines must lie redward of the hydrogen Lyα wavelength $\lambda = 1216\,\AA$, in order to avoid confusion with the lower-redshift Lyα forest. In this paper, I suggest metal absorption lines as a probe of the neutral IGM. Metals are a natural probe: for a fully neutral IGM, $\tau_{\rm H\,Ly\alpha} \sim 10^5$ at $z \sim 6$, and while the oscillator strengths of metal UV/optical transitions ($f \sim 10^{-2} - 1$) are roughly comparable to that of hydrogen Lyα, the abundance by number of metals should be lower by $\sim 10^{-6} - 10^{-5}$, implying $\tau_{\rm metals} \sim 10^{-2} - 1$. The most uncertain aspect of this calculation is the degree to which an IGM polluted by metals can still remain neutral. I argue that because overdense regions are the first to be polluted with metals but the last to be permanently ionized (due to the short recombination time), a scenario of a neutral but metal-polluted IGM is plausible. Nonetheless, because of this uncertainty, a null detection of absorption will only yield a constraint on the joint metallicity/ionization state of the IGM. A positive detection, however, may be our best hope of unveiling an almost fully neutral IGM with observations of high-redshift quasars in the near future. In all numerical estimates, I assume a ΛCDM cosmology with $(\Omega_M, \Omega_\Lambda, \Omega_b, h, \sigma_{8h^{-1}}, n) = (0.35, 0.65, 0.04, 0.65, 0.87, 0.96)$.

2 CAN METALS BE SEEN AT HIGH REDSHIFT?

It is useful to begin by ruling out some promising possibilities. The best absorption line probes would involve promordial elements, which are not afflicted with uncertainties associated with the (unknown) high-redshift metal abundance. The most obvious candidate, hydrogen 21 cm absorption, has too weak an oscillator strength, the optical depth across a Hubble volume is $\tau = 4.2 \times 10^{-3} \left\langle x_{\rm HI} \right\rangle \left(\frac{T_{\rm CMB}}{T_{\rm S}}\right) \left(\frac{1+z}{7}\right)^{1/2}$ (where $T_{\rm S}$ is the spin temperature), and the observational difficulties in detecting a signal are formidable[1] (Shaver et al 1999). Similarly, H_2, which lacks a dipole moment, has too low an oscillator strength. HD does have a dipole moment and higher oscillator strengths (by a factor of ~ 1000) but insufficient to offset its low primordial abundance $x_{\rm HD} \sim 10^{-7}$. Likewise, the optical depth of lithium is appreciable only at high redshift $z \sim 500$ (Loeb 2001). Deuterium has roughly the right abundance ($\sim 10^{-5}$) and oscillator strength (same as H), but its Lyα wavelength lies too close to the H Lyα transition (offset by only $\sim 82{\rm km\,s^{-1}}$) to be useful. HeI has a meta-stable state 2^3S state , which becomes populated during the recombination cascade. Resonance-line absorption from this state occurs at long wavelengths $\sim 4471, 5876\,\AA$, which are redward of hydrogen Lyα as required. However, due to the relatively short lifetime, $\sim 10^4$s, of this state, it is appreciably populated only in highly dense and significantly ionized gas: $n(2^3S)/n(He^+) = 5.8 \times 10^{-6} T_4^{-1.18}/(1 + 3110 T_4^{-0.5} n_e^{-1}) \approx 1.9 \times 10^{-9} T_4^{-0.7} n_e$ (Clegg 1987), where n_e is the electron number density in cm^{-3}. The only possibility left is metal lines.

The optical depth of a line across a uniform IGM which has been homogeneously polluted by metals is:

$$\tau = 0.16\, x_i \left(\frac{X_a}{2.7 \times 10^{-6}}\right) \left(\frac{f}{0.05}\right) \left(\frac{\lambda}{1302\AA}\right) \left(\frac{1+z}{7}\right)^{3/2} \quad (1)$$

where x_i is the fraction of the metal atoms a at the appropriate ionization state i, $X_a = Z/Z_\odot \times (n_a/n_H)_\odot$ is the abundance by number of metal a relative to hydrogen, f and λ are the oscillator strength and rest wavelength of the appropriate transition. I adopt $(n_{\rm C,\odot}, n_{\rm 0,\odot}, n_{\rm Si,\odot}, n_{\rm Fe,\odot}) = (3.58, 8.49, 0.33, 0.295) \times 10^{-4} n_{\rm H,\odot}$ for the solar abundance of carbon, oxygen, silicon and iron respectively (Anders & Grevesse 1989). For some metals, particularly Si, this may be an underestimate: the supernovae of supermassive stars which are thought to form out of very low/zero metallicity gas overproduce α elements such as Si, S and Ca by factors of a few compared to solar ratios (Heger & Woosley (2001); see Fig. 1 of Oh et al (2001)). In Table 1, I list various lines which I have identified as promising tracers of the IGM ionization state[2]: those with ionization potentials close to that of hydrogen and strong resonance lines redward of hydrogen Lyα. If the IGM is polluted to a metallicity of $Z \sim 10^{-2.5} Z_\odot$ at $z \sim 6$, the optical depths are fairly high: there would be a flux decrement of $\sim 5 - 20\%$ blueward of these lines, which is certainly detectable in high signal-to-noise spectra. Note that ions with ionization potential $I_i < 13.6$eV may be rare as the universe is optically thin to radiation at these wavelengths and these atoms are very easily ionized to the next stage. Submillimeter fine structure lines of metals have oscillator strengths which are too low for absorption to be detectable. Although (as we shall see) metal line absorption likely produces a fluctuating forest rather than a mean flux decrement, the relative values of τ provide a good estimate of the importance of various transitions.

OI is a particularly promising tracer. Its ionization potential $I_i = 13.618$eV is only $\Delta E = 0.19$eV higher than that of hydrogen : therefore a detection of OI almost certainly signals the presence of neutral hydrogen. In fact, oxygen should be locked in tight charge exchange equilibrium

[1] However, 21 cm *emission* from the neutral IGM might be detectable with the Square Kilometer Array (Tozzi et al 2001)

[2] Tables for the atomic constants are available at http://www.pa.uky.edu~verner/lines.html

Table 1. Metal absorption lines which may potentially be observable in a nearly neutral IGM. I_i is the ionization potential of the ion, λ and f are the absorption wavelength and oscillator strength, and τ is the optical depth of the line across a uniform IGM at $z = 6.3$, assuming a metallicity of $\mathrm{Z} = 10^{-2.5}\mathrm{Z}_{\odot}$. Only the species with $I_i > 13.6$eV (OI, FeII, SiII) are likely to be abundant, since the universe is optically thin to radiation below the Lyman limit.

Ion	I_i (eV)	$\lambda(\AA)$	f	$\tau(z=6)$
FeI	7.87	2484	0.557	0.11
SiI	8.1	2515	0.236	0.05
CI	11.2	1657	0.148	0.23
OI	13.6	1302	0.05	0.14
FeII	16.1	2383	0.3	0.05
SiII	16.34	1260	1.18	0.13

with hydrogen, through the processes $\mathrm{O} + \mathrm{H}^+ \rightarrow \mathrm{O}^+ + \mathrm{H}^o$, $\mathrm{O}^+ + \mathrm{H}^o \rightarrow \mathrm{O} + \mathrm{H}^+$ (Osterbrock 1989). The equilibration timescale is $\sim 1/k_{ce}n_{\rm HI} \sim 1.7 \times 10^5 x_{\rm HI}\Delta\left(\frac{1+z}{7}\right)^3$years (where Δ is the gas overdensity), much shorter than the Hubble time. Therefore the OI fraction should be very accurately given by $\frac{n_O}{n_{O^+}} = \frac{9}{8}\frac{n_{H^o}}{n_p}\exp\left(\Delta E/k_B T\right)$, where $\exp\left(\Delta E/k_B T\right) \rightarrow 1$ for $k_B T \gg \Delta E = 0.19$eV.

The SiII 1260 Å line is another promising absorption feature. Note that SiII has a 1304 Å transition at almost the same wavelength as the OI transition, but due to the weak oscillator strength $f = 0.0871$ it has an optical depth only $\sim 7\%$ that of OI, unless the Si to O ratio is strongly enhanced. Similarly, the $\lambda = 1526$ Å transition of SiII ($f = 0.132$) has $\tau \approx 0.11\tau_{\rm OI}$.

There are two large uncertainties in the above estimates. The first is the mean metallicity of the IGM at high redshift. The very short timescale on which massive stars evolve $\sim 10^6 - 10^7$years implies that the IGM could have been polluted very early. The metal abundance of the quasar environment inferred from spectra of the $z = 6.28$ SDSS quasar is indistinguishable from that of lower redshift quasars; there is little or no evolution in the observed supersolar metallicities from $z \sim 6$ to $z \sim 2$, implying that the first stars around quasars must have formed at $z > 8$ (Pentericci et al 2001). The mean metallicity of the IGM at $z \approx 3$ at the lowest observable column densities is $Z \sim 10^{-2.5}Z_{\odot}$ (Songaila 1997; Ellison et al 2000). From the spectra of 32 quasars in the redshift range $2.31 - 5.86$, Songaila (2001) finds no evolution in the mean universal metallicity of the IGM in the redshift range $z = 1.5 - 5.5$. The *minimum* value she finds at $z = 5$ is $Z > 10^{-3.5}Z_{\odot}$; this is a strictly minimal estimate because it assumes CIV and SiIV are the dominant ionization stages (which may no longer be true at higher redshifts as the metagalactic radiation field drops and gas densities increase); furthermore, lines are substantially undercounted at the highest redshifts because of high noise levels at the longest wavelengths. Very plausible theoretical scenarios can be constructed in which an early generation of stars pollute the intergalactic medium to mean metallicities $Z \approx 10^{-2.5}Z_{\odot}$ with volume filling factors $> 20\%$ by $z \sim 9$, without significant hydrodynamic perturbation of the IGM (Madau, Ferrara & Rees 2001).

In fact, we emphasize that for reionization to take place, a significant amount of star formation and thus metal ejection must take place. Madau & Shull (1996) find that the energy in the ionizing continuum released by stars is $\sim 0.2\%$ of the rest-mass energy of metals produced, or ~ 1.8 MeV per metal baryon; this is fairly independent of the IMF since the same massive stars which produce ionizing photons produce metals. A similar relation holds for supermassive stars $M > 100M_{\odot}$ thought to form out of metal-free gas, which explode as pair-instability supernovae: they eject $\sim$half of their mass as metals (Heger & Woosley 2001), and release 1.8×10^{48} HI ionizing photons $\mathrm{s}^{-1}\,\mathrm{M}_{\odot}^{-1}$ over a lifetime $\sim 3 \times 10^6$yrs (Bromm, Kudritzki & Loeb 2001), which yields ~ 3.3 MeV per metal baryon. Using the Madau & Shull (1996) relation and assuming $\sim 20\,$eV per HI ionizing photon, we can write:

$$n_\gamma = 0.7\left(\frac{\bar{Z}}{10^{-2.5}Z_{\odot}}\right)\left(\frac{\rm f_{esc}}{0.1}\right) + \mathrm{n}_\gamma^{\rm QSO} \tag{2}$$

where n_γ is the number of ionizing photons per baryon in the universe, $\bar{Z}$ is the mean metallicity of the universe, $f_{\rm esc}$ is the escape fraction of ionizing photons from their host halos, and $n_{\rm QSO}$ is the contribution from quasars (which produce ionizing photons but no metals). The escape fraction f_{esc} is highly uncertain, with estimates ranging from $\sim 5\%$ in the local universe (Leitherer et al 1995; Dove, Shull & Ferrara 2000) to as high as $\sim 50\%$ in highly luminous Lyman break galaxies (Steidel, Pettini & Adelberger 2001). However, even for $f_{esc} \sim 100\%$, the mean metallicity should be reasonably high toward the tail end of the reionization process, $\bar{Z} \sim 10^{-3.5}Z_{\odot}$. Another uncertainty is the filling factor of metal-polluted regions f_Z. We show in §3 that most reasonable values of f_Z should give rise to an absorption signal. Significant retention of metals by their host halos is unlikely due to the shallow potential wells predominant at these early epochs; in addition metal-enriched material is much more easily ejected from halos than the ambient gas (MacLow & Ferrara 1999). The only case where the universe can be reionized without significant co-production of metals is if quasars are the dominant ionizing source. Again this is highly uncertain, but note that the comoving emissivity of quasars at $z = 5$, as inferred from the quasar luminosity function, is insufficient to keep the universe reionized at $z = 5$ by an order of magnitude (Madau, Haardt & Rees 1999; Fan et al 2001a); the density of quasars at high redshift is also constrained by the lack of faint red unresolved objects in the Hubble Deep Field (Haiman, Madau & Loeb 1999). Except for the very early stages of reionization (which are unlikely to be accessible with present-day instruments, in any case), the IGM is likely to be polluted to sufficiently high metallicity to make metal-line absorption studies feasible.

The second, much larger uncertainty is whether regions which are pre-enriched with metals can still remain neutral. As previously noted, the filling factor of ionized regions should be considerable once the IGM is polluted up to metallicities $Z \sim 10^{-3.5} - 10^{-2.5}Z_{\odot}$, unless the escape fraction is very small $f_{esc} < 1\%$, and it is possible that all metal-polluted regions will also be ionized. Indeed, for $f_{esc} >$ few %, the typical size of HII regions at $z \sim 9$ will be greater than that of the metal-laden supernovae-driven superbubble (Madau, Ferrara & Rees 2001); an ionization front precedes the metal-pollution front. Even if the ionizing-photon escape fraction is extremely small, the metal pollution front is likely to collisionally ionize the IGM by shock heating it to $T > 10^{4.5}$K, due to the high speed of the expanding superbubble.

However, it is important to realize that hydrogen recombination times at high redshift, $t_{\rm rec} \approx 3 \times 10^8 x_e^{-1} \Delta^{-1} \left(\frac{1+z}{10}\right)^{-3} \left(\frac{\rm T}{10^4\,\rm K}\right)^{0.7}$yrs, are short compared to the Hubble time, $t_H = 9 \times 10^8 \left(\frac{1+z}{10}\right)^{-1.5}$yrs, so the ionization fraction, $x_e = 1/(1+(t/t_{\rm rec})) \approx t_{\rm rec}/t_H = 0.3\Delta^{-1} \left(\frac{1+z}{10}\right)^{-1.5} \left(\frac{\rm T}{10^4\,\rm K}\right)^{0.7}$, and the gas could become $\sim$ 70% neutral. The lifetime of sources is likely to be short: the lifetime of massive stars is $t_{MS} \sim 10^6 - 10^7$yrs, and the duty cycle of quasars is probably of order the Eddington timescale $\sim 10^7$yrs (such a lifetime is consistent with current observations of quasars; see Blandford (1999) and references therein). Early reionization in the pre-overlap era is likely a highly stochastic process in which regions of the IGM are ionized, polluted with metals, and then recombine and become largely neutral until another source lights up. While early reionization is temporary and the ionization state of any given region of the IGM fluctuates, metal pollution is a permanent process and the metallicity of the IGM rises monotonically. Note also that although high-density filaments may initially be collisionally ionized by the accretion shock during gravitational collapse, the gas will eventually cool and recombine.

In particular, overdense regions are the first to be polluted up to high metallities (due to their proximity to sites of star formation) but they are the last to remain permanently ionized (due to the short recombination times). From numerical simulations, Cen & Ostriker (1999) find that metallicity depends very strongly on local density: at every epoch, higher-density regions have much higher metallicities than lower-density regions. In fact, the highest-density regions quickly saturate at near-solar metallicities early on. These results are in much better agreement with observations than scenarios in which metal pollution is uniform. Miralda-Escudé, Haehnelt & Rees (2000) point out that in an inhomogeneous universe reionization should begin in voids and gradually penetrate into overdense regions; the regions of highest density are the last to be reionized. This picture is strongly substantiated in numerical simulations of reionization (Gnedin 2000). These arguments suggest that a line of sight to a high-redshift quasar will intersect regions at or above the mean density which are largely neutral but nonetheless polluted with metals. Such overdense regions are the most likely sites to produce the metal absorption lines we seek.

The temperature of metal-polluted gas is likely to be $\sim 10^4 - 10^5$K (Madau, Ferrara & Rees 2001). It can be shock heated up to $\sim 10^7$K by the expanding superbubble, but cools rapidly by Compton cooling off the CMB on a timescale $t_{\rm comp} = 2.3 \times 10^8 \left(\frac{1+z}{10}\right)^{-4}$yrs. Below $T \sim 10^4$K the gas recombines and Compton cooling (as well as hydrogen line cooling) is no longer effective; the gas then cools only

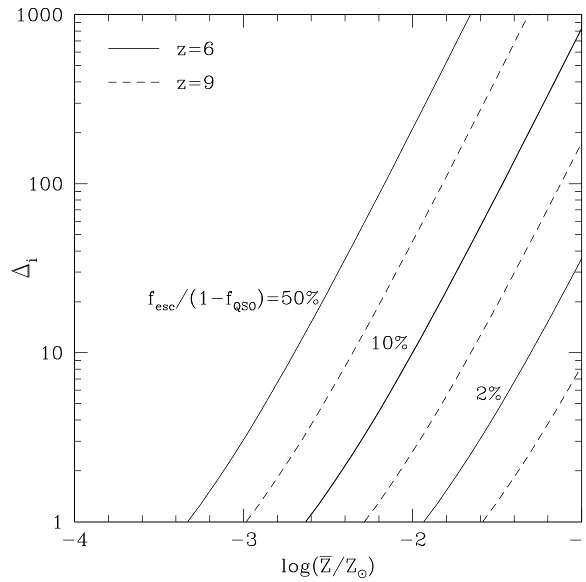

Figure 1. Overdensity Δ_i up to which the universe is ionized in the post-overlap era, as a function of the mean metallicity of the universe $\bar{Z}$, assuming a (fairly robust) relation between the metals and ionizing photons produced by massive stars. Solid lines are for $z = 6$, dashed lines for $z = 9$. The curves are plotted for different values of $f_{\rm esc}/(1 - f_{\rm QSO})$ where $f_{\rm esc}$ is the escape fraction of ionizing photons from star-forming halos, and $f_{\rm QSO}$ is the fractional contribution of quasars to the ionizing background. The relation between Δ_i and $\bar{Z}$ shown here is used in Figure 3.

by adiabatic expansion on the Hubble expansion timescale. In highly overdense and metal-polluted regions metal-lines cooling will become important, but these correspond to collapsed halos which are in any case unstable to star formation. $T \sim 10^4$K is also the equilibrium temperature if a photoionizing background is present.

3 THE OI FOREST

3.1 A simple model for gas clumping and metal pollution

Let us now quantify the effects of gas clumping in the IGM. Miralda-Escudé, Haehnelt & Rees (2000) find the following to be a good fit to the probability distribution by volume of gas overdensities Δ seen in the LCDM numerical simulations of Miralda-Escudé et al (1996):

$$P_V(\Delta)d\Delta = A\exp\left[-\frac{(\Delta^{-2/3} - C_o)^2}{2(2\delta_0/3)^2}\right]\Delta^{-\beta}d\Delta \qquad (3)$$

where they tabulate values for A, β, C_o, δ_o at different redshifts z=2, 3, 4 and 6. One can extrapolate their results to higher redshifts by using $\delta_o = 7.61/(1+z)$ (which fits their results to better than 1%), assuming $\beta = 2.5$ (corresponding to an isothermal slope for high-density halos), and fixing A, C_o by requiring the total mass and volume to be normalized to unity. Their fit is valid if the gas is smoothed on the Jeans scale for a gas temperature $T \sim 10^4$K; we have argued that high-redshift metal-polluted gas should indeed be at approximately this temperature. The fraction of baryons above a given overdensity Δ_i by volume and by mass is then given by $f_{\rm V}(\Delta_i) = \int_{\Delta_i}^{\infty} P_{\rm V}(\Delta) d\Delta$ and $f_{\rm M}(\Delta_i) = \int_{\Delta_i}^{\infty} \Delta P_{\rm V}(\Delta) d\Delta$ respectively.

In order to compute the optical depth of the IGM to metal line absorption we need to specify two unknown functions, the metallicity $Z(\Delta, z)$ and ionization fraction $x_i(\Delta, z)$ of the IGM as a function of overdensity and redshift, but only in the combination $Y(\Delta, z) \equiv x_i(\Delta, z) Z(\Delta, z)$. We can make progress by making some simplifying assumptions. The growth of metallicity has two free parameters: the mean metallicity of the universe $\bar{Z}$ (a proxy for the total amount of star formation), and the volume filling factor of metal-polluted regions f_Z. These two parameters are obviously inter-related, but due to the large uncertainties we treat them as independent free parameters, with an upper bound on the filling fraction $f_Z < 0.2\left(\bar{\rm Z}/10^{-2.5}{\rm Z}_{\odot}\right)^{3/5}$ (where the normalization is based on the model of Madau, Ferrara & Rees (2001), and the exponent mimics the energy dependence of the adiabatic Taylor-Sedov solution). Filling factors as low as $\sim 1\%$ are possible if the metal-enriched ejecta have magnetic fields which resist mixing with the IGM; metal-polluted regions could be restricted to magnetized "streaks" which are then sheared and distorted by subsequent gravitational clustering (Madau, Ferrara & Rees 2001). The growth of reionization has two free parameters, the filling factor Q of ionized regions, and the overdensity up to which gas is ionized Δ_i. Again these parameters are obviously related, but we can make the approximation that they are decoupled, with the following argument. The early stages of reionization are characterized by reionization of the voids ($\Delta_i < 1$) and growth of the filling factor of ionized regions Q. However, at some point overlap occurs ($Q \approx 1$), and overdense regions start to be reionized, and Δ_i grows (this hinges on the fact that high-density regions only occupy a small fraction of the volume). As noted by Miralda-Escudé, Haehnelt & Rees (2000), the value of $\Delta_i^{\rm overlap}$ at which $Q \approx 1$ depends on the nature of the ionizing sources: for dim but numerous sources $\Delta_i^{\rm overlap} \sim 1$, whereas for bright but rare sources $\Delta_i^{\rm overlap}$ is larger, since higher density regions have to be ionized before percolation can occur. We therefore treat it as a free parameter.

The progress of reionization and the growth in metallicity $\bar{Z}$ are coupled via equation (2). In particular, the relation between (Q, Δ_i) and $\bar{Z}$ depends on the escape fraction of ionizing photons f_{esc} and the relative contribution of QSOs to reionization $f_{\rm QSO} \equiv n_{\gamma}^{\rm QSO}/n_{\gamma}$. In the early stages of reionization, recombinations are unimportant and $Q \propto n_{\gamma} \propto \bar{Z}$. In the late stages when recombinations dominate the consumption of ionizing photons, we can relate $\bar{Z}$ and the overdensity up to which gas is ionized Δ_i by equating the number of ionizing photons per baryon with the mean number of recombinations per baryon in a Hubble time of the ionized gas:

$$n_{\gamma}(\bar{Z}) = t_H \alpha \bar{n} C_{\rm HII}(\Delta_i) \quad (4)$$

where $C_{\rm HII}(\Delta_i) = \int_0^{\Delta_i} \Delta^2 P_V(\Delta) d\Delta$ is the clumping factor of ionized gas. This assumes that most star formation and hence metal pollution occured during the last Hubble time. The relationship between Δ_i and $\bar{Z}$ is shown in Fig 1, for different values of $f_{\rm esc}/(1-f_{\rm QSO})$: the smaller the value of this parameter, the larger the amount of star formation and thus metal pollution $\bar{Z}$ needed to keep the universe ionized.

With this simple picture we can make an ansatz for the evolution of $Y(\Delta, z)$. I assume that metal pollution begins in the most overdense regions, while reionization begins in the most underdense regions. At any given epoch, I assume $Z \approx Z_{\rm crit}$ for $\Delta > \Delta_i^{fz}$ and $Z \approx 0$ otherwise. Similarly, I assume the neutral fraction $x_{HI} \approx 1$ for $\Delta > \Delta_i^{HI}$ and $x_{HI} \approx 0$ otherwise. The value of Δ_i^{fz} is given by the implicit equation $f_{\rm V}(\Delta_i) = f_Z$, while $Z_{\rm crit} = \bar{Z}/f_M(\Delta_i^{fz})$. The value of Δ_i^{HI} is $\Delta_i^{HI} < 1$ during the pre-overlap phase and is given by equation (4) in terms of $\bar{Z}, f_{\rm esc}, f_{\rm QSO}$ in the post-overlap phase, when recombinations are important. There are two limits to consider. In the early stages of reionization, when $\Delta_i^{HI} < \Delta_i^{fz}$, the high-density regions where metals reside are largely neutral, $x_i \sim 1$. The growth in Y with time is dominated by the increase in metallicity. This epoch can therefore be characterized by the two parameters $(\bar{Z}, f_Z)$. In the late (post-overlap) stages of reionization, when $\Delta_i^{HI} > \Delta_i^{fz}$, the evolution in Y is dominated by the evolution of x_i, when increasingly dense (and metal-polluted) regions become ionized. In this regime the model can be specified in terms of the parameters $(\bar{Z}, f_z, f_{\rm esc}/(1-f_{\rm QSO}))$, and Δ_i^{HI} can be computed from equation (4). The transition between these two regimes occurs when the volume filling fraction of metal polluted regions and neutral regions are comparable, $f_Z \sim 1 - Q$. Since we expect $f_Z < 0.2$ (metal pollution should not be effective in voids, which occupy most of the volume), the transition regime occurs roughly at the point of overlap, when $Q \rightarrow 1$. The transition occurs very quickly: $1-Q$ evolves extremely rapidly at the point of overlap, when the mean free path of ionizing photons rises on a very short timescale (of order the light travel time across an HII region) and the ionizing background increases dramatically. By contrast, Z evolves on the timescale for structure formation or t_H. In fact, $\dot{Z}$ may drop at the point of overlap since the sudden rise in the IGM temperature and Jeans mass could cause a drop in the comoving star-formation rate (Barkana & Loeb 2000).

In summary, for most of the gas, the parameter $Y \equiv x_i Z$ rises in the early stages of reionization as the metallicity grows, peaks at an epoch roughly correponding to the overlap epoch, and then falls as the gas is reionized. Note that for higher Δ, the peak value of Y is higher and occurs at progressively later epochs, since gas at higher overdensities is only reionized at later times, and so there is a longer time interval for metal pollution to take place. We now examine the observational predictions of this simple model.

3.2 Observational Predictions

We begin by computing the mean Gunn-Peterson absorption in a clumpy and inhomogeneously polluted universe. The optical depth due to regions of overdensity Δ is given by $\tau(\Delta, z) = \Delta \frac{Z(\Delta,z)}{\bar{Z}} \frac{x_i(\Delta,z)}{\bar{x}_i} \tau_o(\bar{Z}, \bar{x}_i, z)$, where τ_o is the optical depth of the line in a uniform IGM which is uniformly

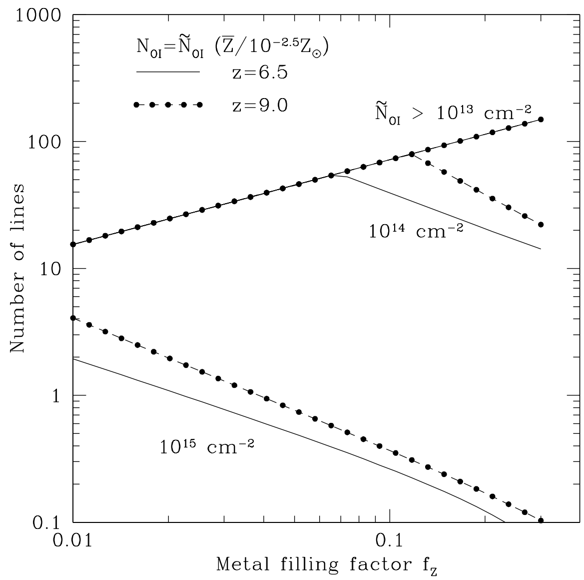

Figure 2. Number of OI lines above a given column density N_{OI} observable in the pre-overlap phase, when metal-polluted high density regions are still largely neutral, as a function of the volume filling factor of metals f_Z. Solid lines are for $z = 6.5$, dashed lines for $z = 9$. The column density scales directly with the assumed mean metallicity $\bar{Z}$. The slope of the relation depends on whether $\Delta_i^{N_{OI}} < \Delta_i^{f_Z}$ (in which case $N_{\rm lines}$ increases with f_Z) or $\Delta_i^{N_{OI}} > \Delta_i^{f_Z}$ ($N_{\rm lines}$ decreases with f_Z). See text for details. The number of observable SiII lines with comparable equivalent widths is roughly half that of OI.

polluted to a metallicity $\bar{Z}$ and has a mean ionization fraction $\bar{x}_i$. The mean metal-line Gunn-Peterson absorption $\mathcal{A}$ due to gas with $\Delta > \Delta_{\rm crit}$ is then given by:

$$\mathcal{A}(\Delta_{\rm crit}) = \left\langle 1 - e^{-\tau} \right\rangle = \int_{\Delta_{\rm crit}}^{\infty} (1 - e^{\tau(\Delta)}) P(\Delta) d\Delta. \quad (5)$$

Note that in general $\mathcal{A}(\Delta_{\rm crit})$ is smaller than $\mathcal{A}$ for a uniform IGM. For instance, for $\Delta_{\rm crit} \sim 3$ at $z = 6$ and $\bar{Z} = 10^{-2.5} Z_\odot$, we have $\tau_{\rm eff} \approx 0.02 x_i$, rather than $\tau \approx 0.14 x_i$ for a uniform IGM. $\tau_{\rm eff}$ falls exponentially with increasing Δ_i, due to the exponentially small fraction of baryons at high overdensities.

The tight charge-exchange equilibrium between OI and HI implies that there is a direct relation between their effective optical depths, *independent* of gas clumping or the nature of the ionizing radiation field:

$$\tau_{\rm OI}^{\rm eff} = 1.1 \times 10^{-6} \left(\frac{\langle Z \rangle}{10^{-2} Z_\odot} \right) \tau_{\rm HI}^{\rm eff}, \quad (6)$$

where $\langle Z \rangle$ is the HI column-density weighted metallicity of the universe (as opposed to the mean metallicity $\bar{Z}$; in general $\langle Z \rangle > \bar{\rm Z}$). Therefore, if we could measure both $\tau_{\rm OI}^{\rm eff}$ and $\tau_{\rm HI}^{\rm eff}$, we can obtain a robust and relatively model-independent measure of the metallicity of the high-redshift universe. Such a fortuitous occasion might arise if we could observe a high-redshift gamma-ray burst, which does not exhibit a strong proximity effect, and therefore allows measurement of $\tau_{\rm HI}^{\rm eff}$ by measuring the shape of the damping wing. The transmitted flux recovers its full value at $\Delta\lambda/\lambda \sim 0.1$ redward of the damping wing (Miralda-Escudé 1998), so a clean separation of the contribution of OI absorption at $1302(1+z_s)$ Å ($\Delta\lambda/\lambda \sim 0.07$) might be possible, particularly if the shape of the damping wing is well-constrained. Although OI absorption will probably produce a fluctuating forest, $\tau_{\rm OI}^{\rm eff}$ can be obtained by smoothing the spectrum. The ability to measure a mean OI decrement of a few percent depends on the accuracy to which sky lines and absorption from other sources can be ruled out (see discussion at end of section). In the absence of a measurement of $\tau_{\rm HI}^{\rm eff}$, a conservative lower bound on the metallicity of the high-redshift universe can still be placed from equation (1) by assuming the IGM to be fully neutral, $x_i \sim 1$, and uniform (since $\langle \tau_{\rm OI} \rangle > \tau_{\rm OI}^{\rm eff}$).

Metals in the high-redshift IGM will probably not produce a Gunn-Peterson-like absorption trough but rather a forest of metal lines which−−particularly in the case of OI−−will provide a snapshot of neutral regions along the line of sight. Schaye (2001) shows that many properties of the Lyα forest can be understood by associating the characteristic lengthscale of absorbers with the local Jeans length. This allows us to associate a column density for an ion i with a given overdensity Δ:

$$N_i = 6.2 \times 10^{13}\,{\rm cm}^{-2}\, x_i \left(\frac{X_a}{2.7 \times 10^{-6}} \right) \left(\frac{1+z}{7} \right)^{1/2} \times \left(\frac{\rm T}{10^4\,{\rm K}} \right)^{1/2} \left(\frac{\Delta}{3} \right)^{1/2} \quad (7)$$

where x_i and X_a are the ionization fraction and metal number abundance. This corresponds to an equivalent width $\left(\frac{W_\lambda}{\lambda}\right) = 5.8 \times 10^{-5} \left(\frac{N_i}{10^{14}\,{\rm cm}^{-2}}\right) \left(\frac{f}{0.05}\right) \left(\frac{\lambda}{1302 \mathring{A}}\right)$, where I have used the fact that lines will always be on the linear portion of the curve of growth. This gives an observed equivalent width

$$W_\lambda \approx 0.53\,\mathring{\rm A} \left(\frac{N_{\rm OI}}{10^{14}\,{\rm cm}^{-2}} \right) \left(\frac{1+z}{7} \right), \quad (8)$$

which is certainly detectable with extended integration on Keck. At a given overdensity Δ the OI 1302 Å and SiII 1260Å equivalent widths are roughly equal; the increased oscillator strength of the SiII line compensates for its reduced abundance. Since on average W_i increases monotonically with Δ, for any given $W_{\rm i}$, there exists some $\Delta_{\rm i}$ such that $\Delta > \Delta_i \Rightarrow W > W_{\rm i}$. The mean spacing between lines with $W > W_{\rm i}$ can be estimated by the mean separation between contours of overdensity Δ_i in the universe. This can be estimated as (Miralda-Escudé, Haehnelt & Rees 2000):

$$\lambda_i = \lambda_o \left[1 - F_V(\Delta_i)\right]^{-2/3}, \quad (9)$$

where $F_V(\Delta_i)$ is the fraction of the volume with $\Delta < \Delta_i$, and $\lambda_o H = 60\,{\rm kms}^{-1}$ (basically determined by the Jeans length) is a good fit to numerical simulations.

There is only a finite stretch of the spectrum over which OI and SiII absorption can be seen before it becomes confused with the hydrogen Lyα forest. Suppose we observe a bright quasar which ionizes its surroundings so that the damping wing of the Gunn-Peterson trough does not extend redward of the Lyα line. A photon can redshift for

$l = \delta\lambda/\lambda \approx 20,000\,\mathrm{km\,s^{-1}}$ from the OI absorption edge at $1302(1+z_s)$Å and $l \approx 10,000\,\mathrm{km\,s^{-1}}$ from the SiII absorption edge at $1260(1+z_s)$Å, before it encounters the HI Gunn-Peterson trough (this interval is actually somewhat smaller, due to the finite width of Lyα and NV emission lines). The average number of lines with $N > N_i$ is $\sim \lambda_i/l$, while the probability that no lines with $N > N_i$ are seen is $\exp(-\lambda_i/l)$.

In Figure 2, we show the mean number of OI lines above a given column density $\tilde{N}_{\rm OI}$ detectable in the pre-overlap phase. In this phase, $(\bar{Z}, f_Z)$ are free parameters. For a given f_Z, the column densities can be rescaled to the assumed mean metallicity via $N_{\rm OI} = \tilde{N}_{\rm OI}\left(\frac{\rm Z}{10^{-2.5}{\rm Z}_\odot}\right)$. We see that $\sim$few lines can be seen in the $10^{14} - 10^{15}\mathrm{cm^{-2}}$ range in the pre-overlap era for filling factors $f_Z \sim 10\%$. Somewhat more lines can be seen at higher redshift since $N_i \propto (1+z)^{1/2}$. The two distinct slopes in the relation can be easily understood. For a given $\bar{Z}$, increasing the metal-filling factor f_z increases the number of patches along a line of sight to a quasar which are metal-polluted, but decreases their mean metallicity $Z_{\rm crit}$. For a low column density threshold, the former effect dominates and $N_{\rm lines}$ increases with f_Z; for a high column density threshold, increasing f_Z increases the number of lines which fall below threshold, and $N_{\rm lines}$ decreases with f_Z.

Similarly, in Fig. 3 we plot the number of lines which can be seen in the post-overlap era at redshift $z = 6$. The relation between $\bar{Z}$ and Δ_i shown in Fig. 1 has been assumed. The different lines illustrate the effect of varying the model parameters around the fidicial model $(f_{\rm esc}, f_{\rm Z}, N_{\rm OI}^{\rm crit}) = (0.1, 0.1, 10^{15}\mathrm{cm^{-2}})$. Again, the change in slope can be easily understood: as the ionized overdensity Δ_i increases the number of lines seen initially increases, because of the larger implied star-formation rate and thus higher $\bar{Z}$. At some point the decrease in filling factor of neutral regions overwhelms the increase in metallicity, and the number of lines decreases. The overdensity Δ_i at which this break occurs depends on $f_{\rm esc}/(1-f_{\rm QSO})$ and f_Z, since these parameters control the relationship between Δ_i and $Z_{\rm crit} = \bar{Z}/f_Z$. For instance, the universe is ionized up to a much higher Δ_i for a given $\bar{Z}$ if $f_{\rm esc}/(1-f_{\rm QSO})$ is large. We see that it is quite plausible for us to see OI absorption lines with observed equivalent widths $W_\lambda \approx 5.3\,\AA\left(\frac{N_i}{10^{15}\,\mathrm{cm^{-2}}}\right)\left(\frac{1+z}{7}\right)$ Å in the SDSS $z = 6.28$ quasar, which lies just at the tail end of reionization Δ_i $\sim$few.

Interesting (though model-dependent) constraints on $\bar{Z}, f_{\rm esc}, f_{\rm QSO}$ and $f_{\rm Z}$ might be possible from measurements of the OI forest. For instance, the length of the dark region and upper limit on the transmitted flux in the Lyα,β troughs give constraints on Δ_i for a given model of structure formation; Fan et al (2001b) find for their $z = 6.28$ quasar that $\Delta_i \sim 3$. From Figure 1 we see that this implies $\bar{Z} \approx 10^{-2.4} Z_\odot\left(\frac{f_{\rm esc}}{0.1}\right)\left(\frac{1-f_{\rm QSO}}{1}\right)^{-1}$, fairly high metallicities. From Figure 3 the number of OI lines above a given column density in the post-overlap phase depends on $f_Z, f_{\rm esc}$; the observed number might constrain their value. The universe is likely to be in the pre-overlap era if a very long Gunn-Peterson trough with no detectable flux is seen. From Figure 3, the number of detectable lines above a given column density might constrain $\bar{Z}, f_Z$. The numerical value of the constraints are of course very model-dependent and should not be over-interpreted. Still, some interesting statements might still be made with reasonable confidence. For instance, if no OI lines can be seen in the post-overlap era despite a deep Gunn-Peterson damping trough, then $\bar{Z}$ is low: this implies the escape fraction of ionizing photons is close to unity and/or quasars are the dominant ionizing source. Alternatively, the majority of the metals are highly ionized, either because most metals reside in voids (although this is unlikely given the finite speed at which metal pollution fronts can propagate), or the high-density regions in which they reside are constantly illuminated by an ionizing source.

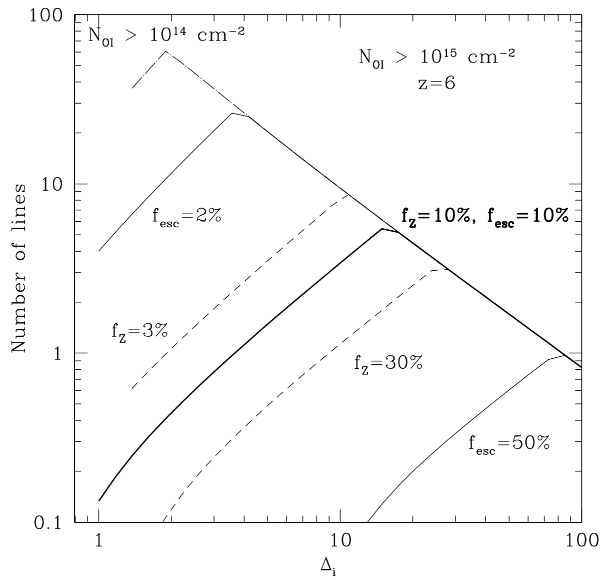

Figure 3. Number of OI lines with $N_{OI} > 10^{15}\mathrm{cm^{-2}}$ observable in the post-overlap era at $z = 6$ as a function of Δ_i, the overdensity to which the IGM is assumed to be ionized. The fidicial model (shown in bold) is for $f_Z = 10\%, f_{\rm esc} = 10\%$ (for a substantial QSO contribution, $f_{\rm esc}$ should be replaced with $f_{\rm esc}/(1-f_{\rm QSO})$). Other lines show the effect of varying $f_Z, f_{\rm esc}$ and N_{OI}. The break in the slope of the relation can be easily understood; see text for details. The number of observable SiII lines with comparable equivalent widths is roughly half that of OI.

The main observational obstacle to detecting the OI forest is confusion with other sources of line absorption. Intrinsic absorption within the quasar host can be constrained by the relative absence of absorption features in the rest frame $1216-1302$Å range of the large sample of lower redshift quasars. Indeed, because of the reasonably wide wavelength interval in which OI and SiII absorption can be seen ($\sim 20,000\mathrm{km\,s^{-1}}$ and $\sim 10,000\mathrm{km\,s^{-1}}$ respectively), at the shorter wavelengths within this range intrinsic absorption can be ruled out. Broad absorption line (BAL) quasars could have winds which show such features, though usually the outflows are highly ionized. Confusion with long wavelength metal lines such as CIV or MgII from lower-redshift systems is another problem. Such an origin can be constrained by the absence of a damped-Lyα system at the corresponding redshift in the low redshift Lyα forest. The third and potentially most serious problem is the fact that the night sky becomes increasingly noisy at these near-IR wavelengths, and the atmospheric OH forest becomes important. The accuracy with which the OI forest can be detected therefore depends on the accuracy with which telluric features can be divided out via a standard-star calibration. Also, there are stretches between the night sky OH forest lines in which no absorption should be seen, so OI absorption can be identified if it falls within these regions. Ultimately, the presence of neutral gas can be corroborated with simultaneous detections of OI, SiII and possibly FeII absorption features. A larger quasar sample which shows long stretches of complete HI Gunn-Peterson absorption and in which the density of OI and SiII absorption features is higher in higher redshift quasars should be an unambiguous signature of almost fully neutral patches of gas at high redshift.

4 DISCUSSION

The SDSS 1030+0524 quasar at $z = 6.28$ shows tantalizing absorption features blueward of the OI 1305Å line (Becker et al 2001). There also appears to be a fairly deep absorption feature blueward of the SiII 1260$\AA$. Could the absorption lines described in this paper been seen already? Unfortunately, the quasars SDSS 1044-0125($z = 5.80$), 0836+0054($z = 5.82$),1306+0356($z = 5.99$) also show some absorption features in the same wavelength interval; in particular, SDSS 1306+0356 shows a very strong absorption feature at $\sim$ 7130Å, with no detected flux over $\sim$ 80Å (this has been tentatively identified as CIV absorption at $z = 4.86$). These features cannot correspond to OI absorption lines: unless they correspond to regions of anomalously high metallicity, the associated hydrogen column densities would be $N_{HI} > 10^{20}\mathrm{cm}^{-2}$, and all flux at the hydrogen Lyα wavelength should be obliterated, while some flux is still seen there. These lines are probably associated with metal lines (e.g. MgII) from lower redshift absorbers, and illustrate a generic difficulty in observing the features proposed in this paper. On the other hand, OI lines are not ruled out in the $z = 6.28$ quasar because of the complete damping of flux at Lyα, Lyβ wavelengths. As we have seen, these absorption features can still arise in the post-overlap epoch when regions with $\Delta >$ few are largely neutral; indeed, up to a few absorption lines with observed equivalent widths $W_\lambda \sim 5\left(\frac{1+z}{7}\right)\left(\frac{N_i}{10^{15}\,\mathrm{cm}^{-2}}\right)$ Å might be seen. Note that the spectra of Becker et al (2001) have been smoothed to 4Å pixel^{-1}. The absorption features blueward of OI 1305Å cannot be definitely identified as OI absorption. Two of them lie at the same wavelengths as bright sky emission lines and are probably due to imperfect sky subtraction. A third line with observed frame equivalent with $\sim 25\,\AA$ is a possible candidate; however, it lies very close to the rest frame OI wavelength and could be due to intrinsic absorption. More cannot be said without careful study of the spectrum. A definitive detection of the OI forest can probably only be done with much higher signal-to-noise spectra of the same quasar.

The estimates in this paper can be addressed with in much greater detail with numerical simulations. In particular, I used very simple ansatzes for the dependences of metallicity and ionization fraction with overdensity, $Z(\Delta), x_i(\Delta)$ which in fact should be highly stochastic and spatially varying. They can be much better modelled in a self-consistent fashion in simulations which attempt to model the metal pollution (Cen & Ostriker 1999; Aguirre et al 2001) and radiative transfer (Gnedin 2000; Razoumov et al 2001), particularly since the rise in metallicity and ionization fraction are inter-related. The spatial structure of the OI forest can be computed by shooting lines of sight through a simulation box. If the OI forest is indeed seen, such studies will be urgently needed to provide a more realistic interpretation of the observations.

The scenario in this paper is not significantly altered if a substantial X-ray background due to high redshift supernovae (Oh 2001) or quasars (Venketesan et al 2001) is present. The large mean free path of hard photons means that they can ionize the IGM fairly uniformly, but beyond $x_e \sim 0.1$ most of the energy of an energetic electron created goes into Coulomb heating the gas rather than collisional ionization (Shull & van Steenberg 1985); predominantly neutral regions should therefore still exist.

We will gain a wealth of information about early metal pollution and the reionization process if the OI and SiII forests are seen. They will be direct probes of the topology and history of gas clumping, metal pollution and reionization in the early universe. As we have seen, if we assume a relation between the metals and ionizing photons produced by massive stars, they could potentially also provide indirect constraints on the escape fraction of ionizing photons from star forming halos and the QSO contribution to the ionizing background, and the filling factor of metal pollution. They may also give clues as to the nature of the ionizing sources: the structure of forest lines should look different if the universe were reionized by rare but luminous source as opposed to abundant but faint sources, since in the former case higher overdensity regions have to be ionized before overlap can be achieved. OI and HI will be locked in very tight charge exchange equilibrium at high redshift. If we are lucky enough to observe the rest-frame optical afterglow of a high-redshift gamma-ray burst and measure both $\tau_{\rm HI}^{\rm eff}$ (from the damping wind) and $\tau_{\rm OI}^{\rm eff}$, we will have a direct measure of the mean metallicity of the universe at high redshift, independent of gas clumping or the form of the ionizing radiation field. Otherwise, a lower limit on the metallicity from measurement of $\tau_{\rm OI}^{\rm eff}$ alone is possible. A null detection of the OI, SiII forests will yield constraints on the parameter $Y_i(\Delta) = x_i(\Delta)Z(\Delta)$, but a positive detection will be tremendously exciting and almost certainly signal the presence of almost fully neutral hydrogen at high redshift. To date, the OI and SiII forests may be our only probes of nearly neutral gas in the pre-reionization epoch observable with current technology.

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